SOLAR PHOTOVOLTAIC ELECTRICAL POWER SYSTEM APPLICATIONS FOR NASA CENTERS

LANGLEY
IN-44-CR

NASA CONTRACT NO. NAS1-14387
TASK ORDER NO. 25, PART A
FINAL REPORT

(NASA-CR-182781) SOLAR PHOTOVOLTAIC ELECTRICAL POWER SYSTEM APPLICATIONS FOR NASA CENTERS Final Report (Grumman Aerospace Corp.) 19 p

N90-70576

Unclas
00/44 0140924

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HEADQUARTERS, MAINTENANCE AND OPERATIONS DIVISION
WASHINGTON, D.C. 20546

PREPARED BY
GRUMMAN AEROSPACE CORPORATION
ENERGY CONSERVATION SERVICES,
FACILITIES ENGINEERING DEPARTMENT
BETHPAGE, NEW YORK 11714

JULY 1978

#140924

SOLAR PHOTOVOLTAIC ELECTRICAL POWER SYSTEM APPLICATIONS FOR NASA CENTERS

NASA CONTRACT NO. NAS1-14387

TASK ORDER NO. 25 PART A

PREPARED FOR

NATIONAL AERONAUTICS & SPACE ADMINISTRATION

HEADQUARTERS, MAINTENANCE AND OPERATIONS DIVISION

WASHINGTON, D.C. 20546

PREPARED BY

GRUMMAN AEROSPACE CORPORATION

ENERGY CONSERVATION SERVICES

FACILITIES ENGINEERING DEPARTMENT

BETHPAGE, NEW YORK 11714

PHOTOVOLTAIC TASK MANAGER: S. WINKLER

JULY 1978

TABLE OF CONTENTS

INTRODUCTION

As an additional effort under the NASA Headquarters Task Order No. 25, we were requested to assist ten NASA Centers in their preparation of proposals for solar photovoltaic applications. We made several telephone contacts to each center. Some centers required considerable assistance. Three centers had detailed analyses. One center could not justify any photovoltaic projects. Most of the estimates of system performance for a given size were considerably inflated. All used different costing baselines. Our task was to differentiate among the four types of electrical load being satisfied:

- o AC, with battery storage
- o DC, with battery storage
- o AC, no storage
- o DC, no storage,

and to use a unified costing approach. There are ratios of 1.1:1 to 3.1:1 or higher in rating of solar array required to meet a given power output, and a 54% to 92% range of system efficiency in use of the solar produced electric energy, depending on which of the four load types is being supplied.

A unified costing and payback approach was hammered out among Dr. Rosenbloom of Lewis Research Center and Mr. Hadjidakis, and the author, which is explained in Section II of this report. The payback analysis uses the life cycle costing approach in which it is assumed that the differential annual escalation rate test of energy cost (over the general inflation rate) exceeds the desired return on invested money, by 10%.

The nine centers for which we assembled load data and calculated the photovoltaic systems' performance, size, costs and paybacks are:

- ARC - Ames
- DFRC - Dryden
- JPL, Jet Propulsion Labs, Pasadena
- JPL, Jet Propulsion Labs , Goldstone
- KSC, Kennedy
- LaRC, Langley
- MSFC, Marshall
- MAF, Michoud
- NSTL, National Space Technology Labs

It must be kept in mind that this report represents a top cut analysis of the photovoltaic systems for the applications selected by the centers. It is certain that with a better understanding of the systems efficiency and array sizing implications of which types of loads are being supplied, a better mix of candidates might be found.

Criteria for selecting sites with good payback times for photovoltaic applications are incorporated in the following candidate characteristics:

- Remote sites - such as mountain tops, small islands, buoys, and uninhabited regions - where the cost of delivering conventional energy is high.
- Loads which peak during the middle of the day, are sun-sensitive, and are low or non-existent at night, requiring no battery storage.
- Locations where the electrical energy costs include either or both of: time-of-day metering and demand changes which penalize daytime energy usage and power demands in the summer, and where the electric rates are high, and the center's total electrical demand peak occurs in day time.
- Loads which require direct current.

None of the sites selected met all these criteria; the rate structures of each of the local utilities which were not available, would have to be studied. It is understood that the criterion of remote site for these photovoltaic applications violates another criterion requested by NASA Hq that these projects have high visibility; this would have to be traded off against the reduced payback for remote sites where electricity may cost \$0.10 to 0.25 per kilowatt-hour, instead of the \$0.01 to \$0.04 for the centers selected.

It should be noted that these solar photovoltaic projects can become much more attractive in payback times, if a circulating fluid loop, air or water, behind the solar cells, is used for thermal applications.

Section 1

PHOTOVOLTAIC SYSTEM TYPES AND PERFORMANCE

Solar Photovoltaic (P/V) Power Systems were selected at the eight NASA Centers, for two general types of applications:

- o Round-the-clock, constant magnitude loads such as battery chargers and cathodic protection circuits.
- o Varying magnitude, peaking in daytime, loads.

Within each of these types, the loads may be either:

- o Alternating Current (AC), or
- o Direct Current (DC).

The round-the-clock loads typically call for a P/V system with battery storage. The daytime-peaking loads can be supplied most cost-effectively with no battery storage - the P/V arrays' power output reduces the peak center electrical demand.

This gives four types of P/V systems listed in order of increasing efficiency, to be used:

Type of System	* System Efficiency	Solar Array Power ** To Load Power Ratio
1) AC - with storage	0.54	3.1
2) DC - with storage	0.64	2.6
3) AC - no storage	0.78	1.3
4) DC - no storage	0.92	1.1

NOTES:

*System efficiency is the ratio of the energy delivered to the load by the P/V system, to the energy out of the solar P/V arrays.

**This is the ratio of the required average solar array output to the load power. The load power is the steady power required by the load in the systems with battery storage. It is the peak power delivered to the load in the no-battery-battery storage cases. The array is sized for the June 21st sun-time, and array temperature. Note that increasing the solar cell temperature from the 77° spec purchase value, reduces the power output by 1.7% for every 10°F of temperature increase.

Section 2

COSTS

2.1 1980 COSTS

2.1.1 Solar Cells

$11/peak watt; "peak watt" is produced at 25°C (77°F.), with insolation of 100 milliwatt/sq. cm (92.9 W/sq. ft.).

2.1.2 Balance of System

$11/peak watt, including:

- o Land clearing and foundation preparation, drainage, gravel (or roof preparation)
- o Interconnecting solar array panels electrically
- o Cooling: plumbing, pumps or fins
- o Supporting structure, security fence, small building enclosure
- o Storage batteries, racks, venting hydrogen, enclosure
- o Solar array output voltage regulators
- o Battery charge/discharge regulators and sensors
- o DC-AC inverters - single phase or 3-phase
- o Frequency-lock and phase-lock to match utility
- o Switchgear, distribution, control circuits, instruments
- o DC-DC converters - single or multiple voltage output

NOTE: This list does not include max. power pt. trackers and geometrical suntrackers or shipping costs.

2.1.3. System Costs for 4 System Types

- o AC, with storage - $22.00/Peak watt
- o DC, with storage - $21.50/Peak watt
- o AC, no storage - $17.50/Peak watt
- o DC, no storage - $17.00/Peak watt

These costs are based on reducing the $22.00/peak watt figure for those equipments not required, as appropriate:

- o Batteries at $70.00/KW-HR, in a 1-day storage design, cost $3.60/peak watt in the system
- o DC-AC inverter at $125 - $500/KW = $0.50/watt
- o Battery charge/discharge regulator and sensors $500 - $900/KW = $0.90/watt

2.2 1982 COSTS

2.2.1 Solar Cells

$2.00/peak watt (DOE Prediction)

2.2.2 Solar Cell Structure, Interconnects, Cooling

$1.50/peak watt (DOE Prediction)

2.2.3 Battery Costs

$3.60/watt peak, corresponding to $70/KW-HR (DOE figure)

2.2.4 Power Conditioning and Charge Regulator Units Costs

- o Assume $100/KW = 0.10/watt for either:
  - AC-DC inverter, or
  - Battery charger/discharge regulator with sensors, or
  - Solar array output regulator
- o Assume any two or three of the above, in combination, cost: $200/KW - $0.20/watt

2.2.5 Total Solar P/V System Costs - (1982)

- o AC, with storage - $7.30/peak watt
- o DC, with storage - $7.30/peak watt
- o AC, no storage - $3.70/peak watt
- o DC, no storage - $3.60/peak watt

2.3 PAYBACK

Payback is based on: $\dfrac{\text{1982 Cost}}{\text{1st Yr.Savings (1980)}}$ = DEF, with energy cost escalation 10% per year above interest cost

NOTE: All above costs increased 25%, for engineering design, inspection and contingencies.

Section 3

ANNUAL INSOLATION AND ENERGY COST DATA FOR NINE NASA LOCATIONS

By direction, the Department of Energy's "DOE Facilities Solar Design Handbook, No. DOE/AD-0006/1" has been used to determine annual insolation. The term "annual insolation" refers to the total energy from both direct specular sunlight and the diffuse sky light falling on a fixed unit area in a typical year. The insolation value for a given geographical location depends on the orientation of the surface. The handbook's Table 4-2 on Page 40, gives monthly and annual values for 31 cities for a surface which faces southwards (in the northern hemisphere) and is tilted at an angle to the horizontal of ten degrees greater than the local latitude angle (which favors winter insolation by a few percent). The cities nearest to the nine NASA sites were selected from this list, with the exception of MAF, NSTL, (New Orleans, nearest city to both), and JPL-Goldstone, (Las Vegas, nearest city). For these sites, the mean (annual) daily solar radiation map, Figure 4-1, on page 42 was used; New Orleans receives 347 Langleys per day, Lake Charles receives 418 Ly/day, Las Vegas receives 509 Ly/day, Davis receives 431 Ly/day. Since the annual insolations of 580,000 BTU/Yr - SF and 680,000 BTU/Yr. -SF are given for Lake Charles, La. and Davis, Cal. respectively on Table 4-2, op. cit., we estimated the insolations at MAF-NSTL and JPL-Goldstone as:

$$\frac{347}{418} \times 580{,}000 = 481{,}000 \text{ BTU/Yr. - SF, and}$$

$$\frac{509}{431} \times 680{,}000 = 803{,}000 \text{ BTU/Yr. - SF, respectively.}$$

The following table summarizes for each NASA center, the insolation on a fixed array tilted at Lat $+10^{\circ}$ in two sets of units:

Thousands of BTU/Yr. - SF

KW - Hr./SF,

and gives the nearest city, latitude, and 1980 electrical energy cost.

ANNUAL INSOLATION DATA AND 1980 ENERGY COST DATA, FOR THE NINE CENTERS

Center	Nearest City in DOE * Solar Manual	Annual Sunlight (Insol. Energy) 10^3 BTU/Yr.Sq.Ft.	KW-HR/SF	Latitude Deg. North	1980 Electricity Cost $/KW-HR
Ames	Davis, Cal.	680	199	38	0.0302
Dryden	Santa Maria, Cal.	751	220	36	0.0176
JPL	Los Angeles, Cal.	665	195	34	0.0349
JPL/ Goldstone	Las Vegas, Nev.	803 *	235	35	0.035
Kennedy	Miami, Fla.	617	181	28	0.0312
Langley	Charleston, S.C.	598	175	37	0.0390
Marshall	Nashville, Tenn.	564	165	35	0.0265
Michoud	New Orleans, La.	481*	141	30	0.0320
NSTL	New Orleans, La.	481*	141	30	0.0302

* "DOE Facilities Solar Design", #DOE/Ad-0006/1, pp. 40 and 42.

Section 4

ANNUAL SAVINGS

The annual savings in electrical utility costs are calculated for two cases:

- o The load is round-the-clock and storage batteries are used.
- o The load is sunlight sensitive, peaking in the daytime and the utility energy and/or demand rates are based on time-of-day metering, for a center in which the total demand peaks in the daytime.

For the first case, the savings are referred to as "averaged" in that the annual savings is dependent on the average annual cost per kilowatt hour. In the second case, because solar P/V reduce the peak demand of the center, the savings are called "demand"; here we have assumed that these time-of-day savings are twice those based on the annual average energy cost.

The expression for annual savings is as follows:

$$SAV = \frac{(Qann) \times (Eov) \times (Esp) \times (Par) \times (Cel)}{(3413) \times (Psp)},$$

where: SAV - is the annual savings, in $ / YR.

Qann - is the annual insolation on a fixed array facing south and tilted at an angle to the horizontal 10 degrees greater than local latitude, in BTU/YR-SF.

Eov - is the overall efficiency of the electrical system from the D C output of the solar array to the input to the load distribution line.

Esp - is the efficiency of conversion of the solar panels from sunlight to D C electricity, with all degradation factors included.

Par - is the peak solar array D C power output, in watts.

Cel - is the unit average annual cost (1980) of electrical energy, in $ / KW-HR.

Psp - is the power output per unit area of the solar panels, in watts/SF.

Taking the KSC Project No. 8 (See Table, Page 9) as an example:

Qann = 617×10^3 BTU/YR-SF; Eov = 0.78; Esp = 0.076;

Par = 52,000 watts; Cel = \$0.0312/KW-HR; Psp = 6.43 Watts/SF;

$$\text{SAV} = \frac{(617 \times 10^3)\ (0.78)\ (0.076)\ (52{,}000)\ (0.0312)}{(3413)\ (6.43)} = \underline{\underline{\$2710/\text{YR.}}}$$

Section 5

SUMMARY OF PRELIMINARY PHOTOVOLTAIC POWER SYSTEMS' SIZING AND COST DATA

In this section are summarized the following parameters of the photovoltaic power systems:

- Project number
- NASA Center
- DC or AC loads
- Battery Storage Requirement - Yes or No
- Energy Efficiency of the system, from solar array electrical outputs to load distribution input
- Steady (around-the-clock) load power requirement with systems using batteries, KW
- Load peak power in "no battery" systems, KW
- Solar photovoltaic array power output, KW
- Annual local insolation of fixed southward-pointing tilted array at tilt angle of latitude-plus-10-degrees to the horizontal, in thousands of BTU of sunlight per year per square foot of array.
- 1980 system cost per peak (solar P/V) array watt, $/watt
- 1980 system cost including 25% addition for design, inspection and contingency, K$
- 1982 system cost including 25% addition for design, inspection and contingency, K$
- 1980 annual savings in $/year based on the annual average cost of electricity
- 1980 annual savings in $/year based on the greatest savings occurring in the summer during the day, for those sites which pay a premium for summer daytime demand and/or energy for centers with daytime, summer peaks; the savings is assumed to be double that associated with the average year-round, round-the-clock load and is referred to as "demand" savings

- DEF, Discounted Energy Factor, which is the ratio of 1982 system cost to first year 1980 savings, based on average electric rate.
- DEF, Discounted Energy Factor, same as above, but based on daytime, summer peak rates
- Payback period based on the average savings and a fuel cost escalation 10% greater than the interest cost, in years
- Payback period, same as above, but based on a demand savings
- Minimum and maximum solar array areas
- Project Titles and Descriptions

See the following three Tables for the summary of these parameters.

SOLAR PHOTOVOLTAIC SYSTEMS INFORMATION - PRELIMINARY SIZING & COST DATA

Proj. No.	NASA Center	DC or AC Loads	Battery Storage	Energy Effici-ency, System	Steady Power with Battery Systems, KW	Load Peak Power in-no Battery Systems, KW	Solar P/V Array Power, KW	Annual Local Insolation 10^3 BTU/Yr SF	1980 System Cost Per Pk Watt $/Watt	1980 System Cost, Including 25% Added: Design, Inspection, Conting'y; K $	1982 System Cost Including 25% Added: Engrg., Inspection, Conting'y; K $	1980 Savings Annual, in $/Yr (Averaged)	1980 Savings, Annual, with 2:1 Demand Savings, $/Yr	DEF = Cost - 1982 ÷ Avg Sav. - 1980 Yr	DEF = Cost - 1982 ÷ Demand Sav. - 1980 Yr	* PAYBACK - AVG. Yr	* PAYBACK - DEMAND Yr
1	ARC	DC	Yes	0.64	3	-	7.8	680	21.50	209	71	143	-	496	-	41	-
2	ARC	DC	Yes	0.64	2	-	5.2	680	21.50	140	48	95	-	505	-	41	-
3	DFRC	AC	No	0.78	-	40	52	751	17.50	1140	240	1860	-	129	-	27	-
4	JPL	AC	Yes	0.54	20	-	62	665	22.00	1630	565	2680	-	211	-	32	-
5	JPL	DC	Yes	0.64	2	-	5.2	665	21.50	140	48	269	-	178	-	30	-
6	JPL/GOLD	AC	No	0.78	-	40	52	803	17.50	1140	240	3940	7880	61	30.5	20	14
7	JPL/GOLD	AC	No	0.78	-	30	39	803	17.50	855	190	2955	5910	61	30.5	20	14
8	KSC	AC	No	0.78	-	40	52	617	17.50	1140	240	2710	5420	89	45	23	17
9	LaRC	AC	Yes	0.54	2	-	6.2	598	22.00	170	56	271	-	207	-	31	-
10	MSFC	AC	Yes	0.54	3.9	-	12	564	18.15	372	119	309	-	385	-	38	-
11	MSFC	DC	Yes	0.64	10	-	26	564	21.50	699	238	861	-	276	-	34	-
12	MSFC	DC	Yes	0.64	12.5	-	32.5	564	21.50	874	296	1080	-	274	-	34	-
13	MSFC	DC	Yes	0.64	1	-	2.6	564	21.50	70	24	86	-	279	-	34	-
14	MSFC	DC	Yes	0.64	10	-	26	564	21.50	699	238	861	-	276	-	34	-
15	MSFC	DC	Yes	0.64	5	-	13	564	21.50	350	119	431	-	276	-	34	-
16	MAF	DC	Yes	0.64	17	-	44.2	481	21.50	1190	404	1510	-	267	-	34	-
17	MAF	AC	No	0.78	-	40	52	481	17.50	1140	240	2160	4320	111	56	25	19
18	NSTL	AC	No	0.78	-	35	45.5	481	17.50	995	210	1790	3580	117	59	26	20
19	NSTL	AC	No	0.78	-	20	26	481	17.50	569	120	1021	2042	117	59	26	20
									TOTAL	$ 13,422 K							

SOLAR ARRAY AREAS

NASA Center / Project No:	ARC 1	ARC 2	DFRC 3	JPL 4	JPL 5	JPL/GOLD 6	JPL/GOLD 7	KSC 8	LaRC 9	MSFC 10	MSFC 11	MSFC 12	MSFC 13	MSFC 14	MSFC 15	MAF 16	MAF 17	NSTL 18	NSTL 19
Sq.Ft. Array Area, Min.	1210	810	8090	9640	810	8090	6070	8090	965	2000	4040	5050	405	4040	2020	6880	8090	7080	4040
Sq.Ft. Array Area, Max.	2420	1620	16180	19280	1620	16180	12140	16180	1930	4000	8080	10100	810	8080	4040	13760	16180	14160	8080

NOTE: ALL P/V ARRAYS ARE FIXED, SOUTH-FACING, TILTED TO LATITUDE + 10° OFF HORIZONTAL, EXCEPT NO. 8 WHICH HAS TWO-AXIS SUN-TRACKING.

* PAYBACK BASED ON ASSUMPTION: FUEL COST ESCALATION 10% PER YEAR ABOVE INTEREST COST.

SOLAR PHOTOVOLTAIC PROJECTS

PROJECT NO.	NASA CENTER	PROJECT TITLE	PROJECT DESCRIPTION
1	ARC	Solar P/V System for emergency switchgear actuation systems (4)	Design, procure and install a photovoltaic array with storage batteries & power conditioning units.
2	ARC	Solar P/V to supply cathodic protection for hi-press gas storage pipes - underground	Photovoltaic array, batteries, power conditioning
3	DFRC	Solar P/V system to offload utility supply to integrated support facility	P/V array and power conditioning
4	JPL	Bldg 277 - supply power to thermoelectric lab	P/V array, power conditioning, batteries
5	JPL	Battery charging station for elec. vehicles	P/V array, power conditioning, and batteries
6	JPL/GOLDSTONE	Power for Administration Bldg. G-21 (ECHO)	P/V array and power conditioning
7	JPL/GOLDSTONE	Power for Administration Bldg. G-60 (VENUS)	P/V array and power conditioning
8	KSC	Visitor info center bldg M6-409 - offload utility line	P/V array, power conditioning
9	LaRC	Provide power to energy and envir. monitor sta. Bldg 1247G	P/V array, power conditioning, and batteries
10	MSFC	Power auxiliaries, including pumps to ABS refrig - Bldg 4249	P/V array, power conditioning, & batteries; array mounted to absorber of 50 ft dia parabolic concentrator; C.R. = 500:1
11	MSFC	Power to utility control system Bldg 4207 - DC loads	P/V array, power conditioning and batteries
12	MSFC	Power to the direct current loads in electronics & control lab - Bldg 4487	P/V array, power conditioning and batteries
13	MSFC	Power to dynamic test stand - DC Loads	P/V array, power conditioning and batteries
14	MSFC	DC power to emergency power circuits - Bldg 4200	P/V array, power conditioning and batteries
15	MSFC	DC to cathodic protection to underground piping	P/V array, power conditioning and batteries
16	MAF	Battery charging station for elec. util veh's	P/V array, power conditioning and batteries
17	MAF	Power to offload central utility substation Bldg 350	P/V array, power conditioning
18	NSTL	Power to offload south wing utility substation Bldg 1100	P/V array, power conditioning
19	NSTL	Power to offload computer Bldg 1110's substation	P/V array, power conditioning